“Superflares on Solar-type Stars and Solar Flares, and Their Impacts on Exoplanets and the Earth.”
@ Kyoto university　2016年3月1日（火）-4日（金）

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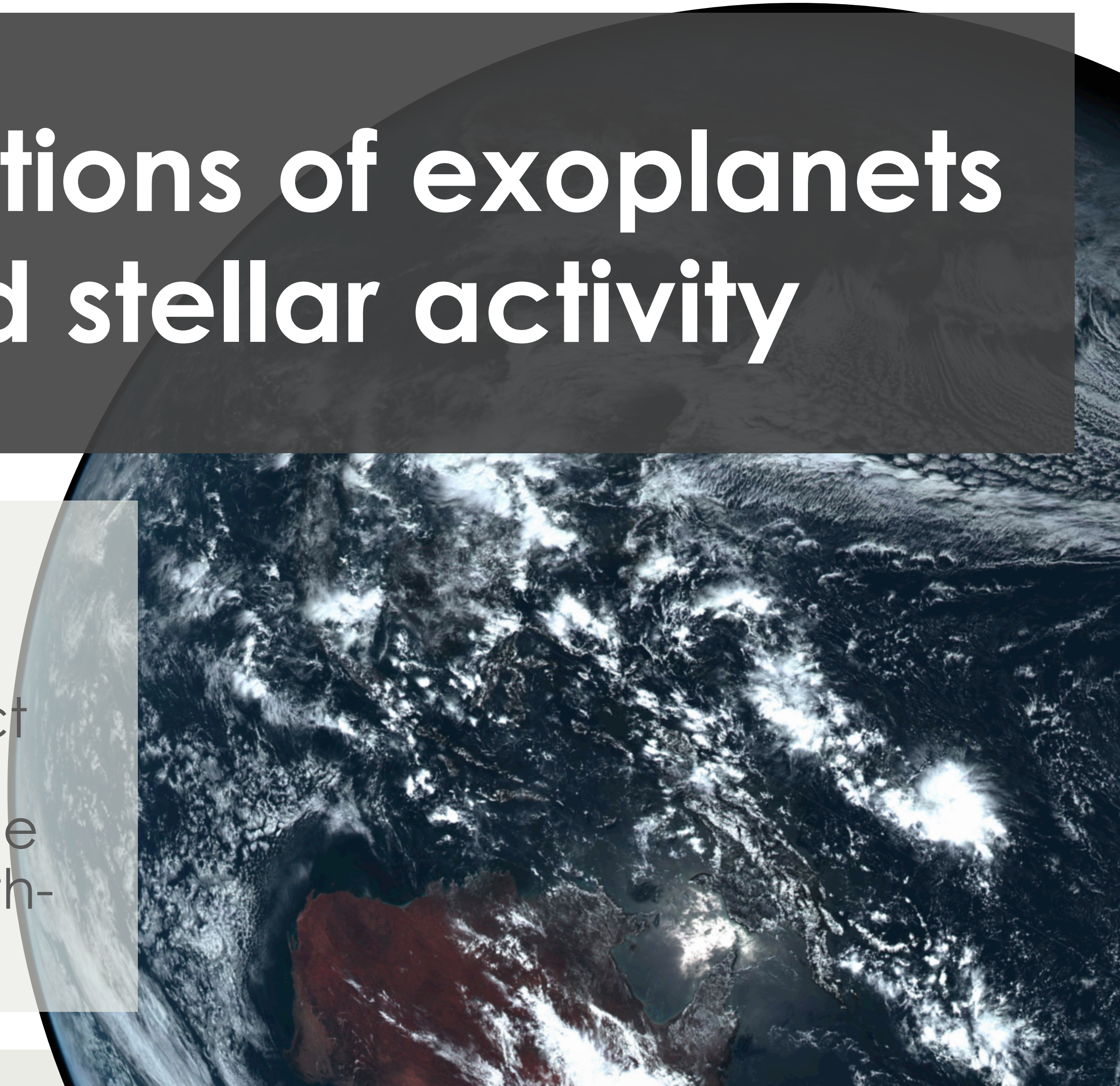
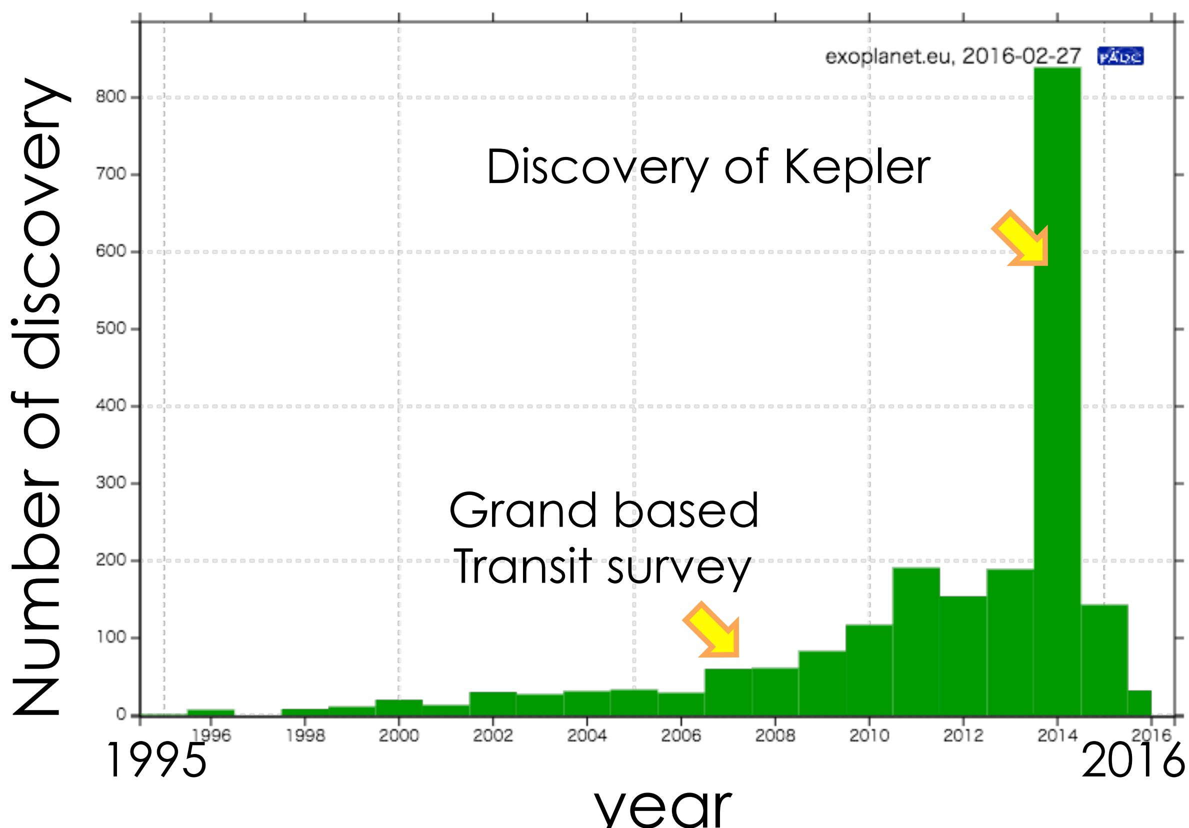
Observations of exoplanets and stellar activity



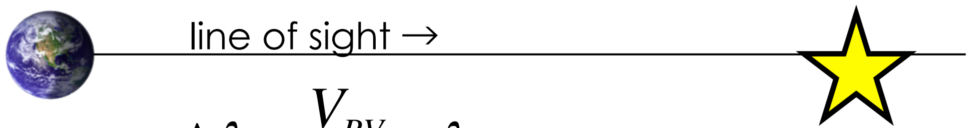
1. Stellar activity on exoplanet searches
2. IRD Doppler project
3. To search for suitable stars to search for Earth-Mass planets

Searches for planets

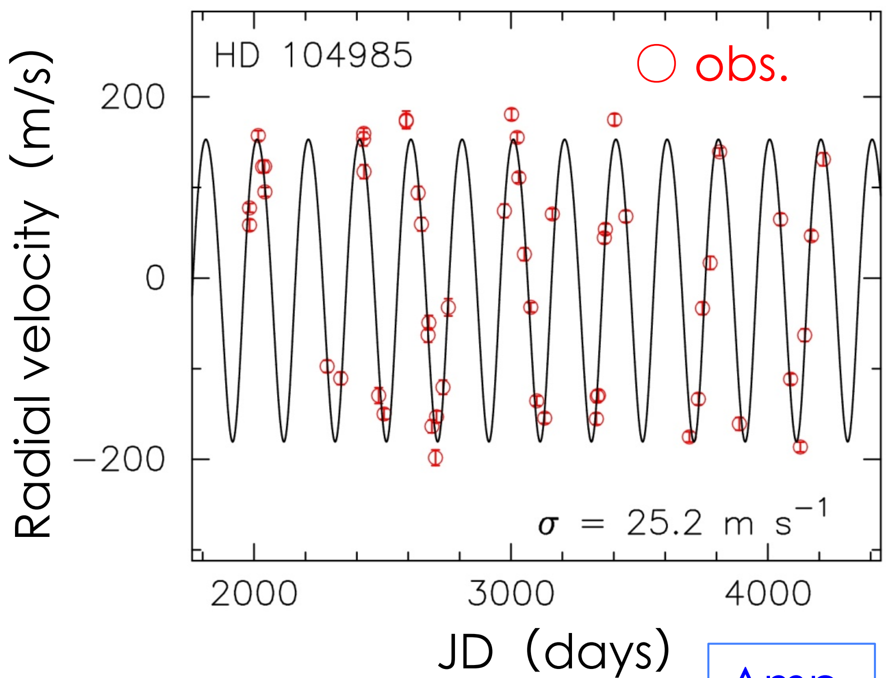
- Since first discovery of an exoplanet around solar type star 51 Peg b, ~2000 exoplanets have been discovered. (Feb. 2016)
  - Mayor & Queloz, Nature, Volume 378, Issue 6555, pp. 355-359, 1995
  - http://exoplanet.eu/
- Simple classification
  - Hot Jupiter
  - Eccentric planets
  - Super Earth
  - Cool Jupiter
- Method of planet sear
  - Doppler
  - Transit
  - Microlensing
  - Astrometry
  - Direct imaging



Detection method : Doppler



$$\Delta\lambda = \frac{V_{RV}}{C} \bullet \lambda$$



- By Dopper method
  - Period P
  - Eccentricity e
  - Amplitude K
- Planetary parameters
  - Mass $M_{star} \sin i$
    - inclination I
  - semimajor axis a

semimajor axis — Mass — Period

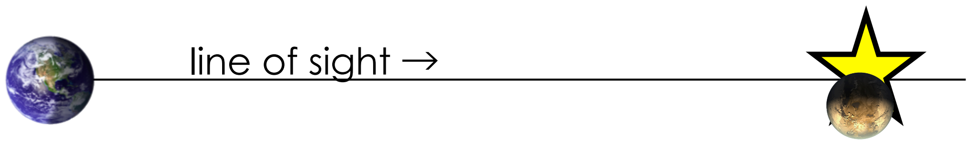
$$\left(\frac{a}{\mathrm{AU}}\right)^3 = \left(\frac{M_{star} + M_{planet} \sin i}{M_{Sun}}\right)\left(\frac{P}{\mathrm{yr}}\right)^2$$

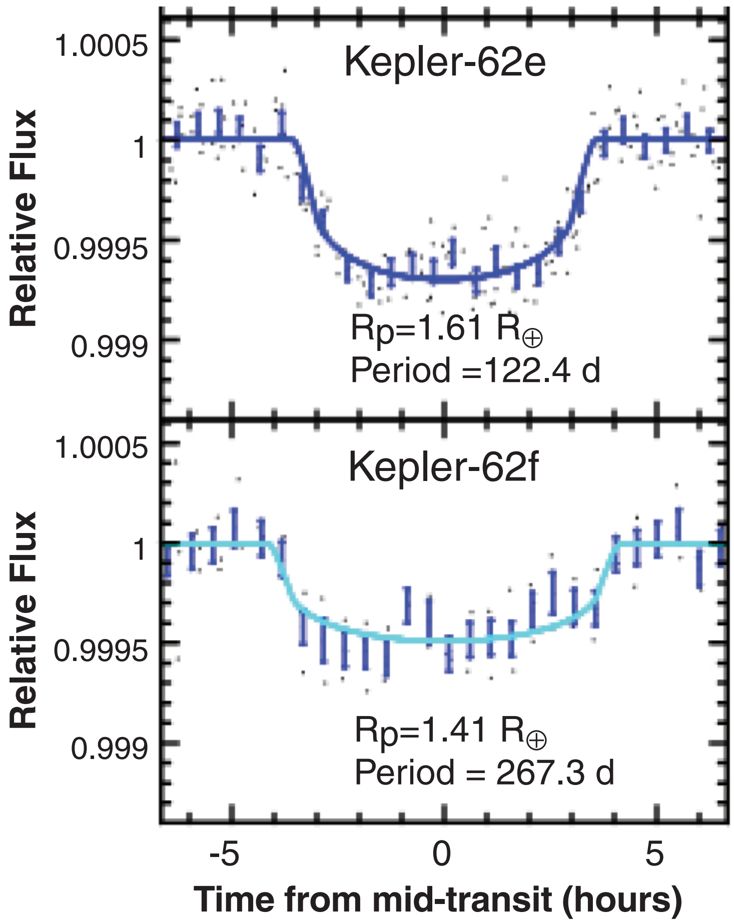
Amp. — Pmass — Period

$$K = \frac{28.4 ms^{-1}}{\sqrt{1-e^2}} \frac{M_{planet} \sin i}{M_{Jup}} \left(\frac{P}{1yr}\right)^{-1/3} \left(\frac{M_{star}}{1M_{Sun}}\right)^{-2/3}$$

Eccen — Stellar mass M_{star}

Detection method : Transit





- By transit method
  - Period P
  - (eccentricity e)
  - Depth of transit
- Planetary parameters
  - Radius R_{planet}
  - Inclination I
  - Semimajor-axis a

Occurrence rate of transit $\sim \dfrac{R_{Star}}{a}$

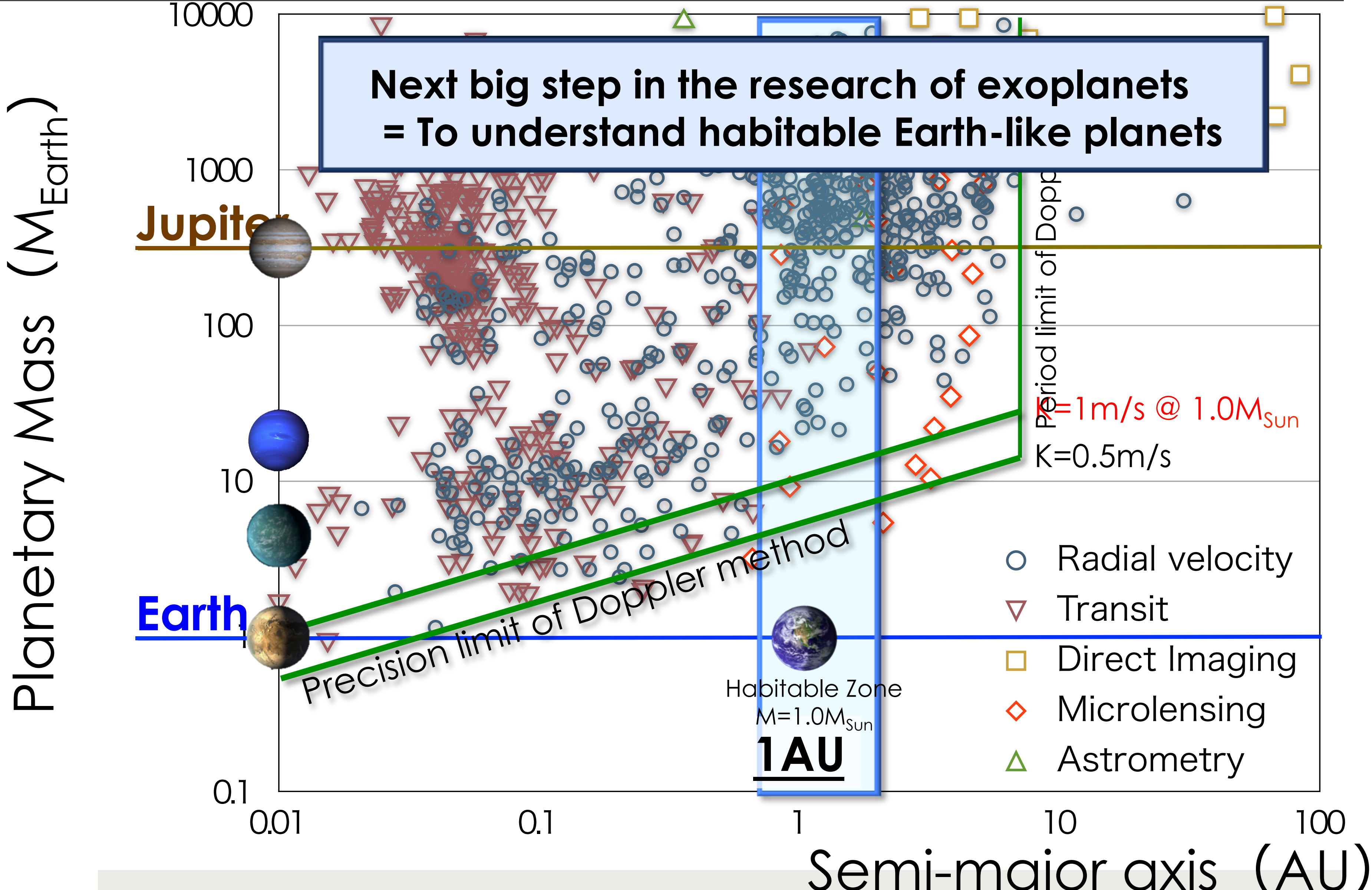
Planet radius

Depth of transit $\sim \left(\dfrac{R_{Planet}}{R_{Star}}\right)^2$

stellar radius R_{star}

Current result: Mass – Semi-major axis

Next big step in the research of exoplanets
= To understand habitable Earth-like planets



Reject Detections of exoplanets

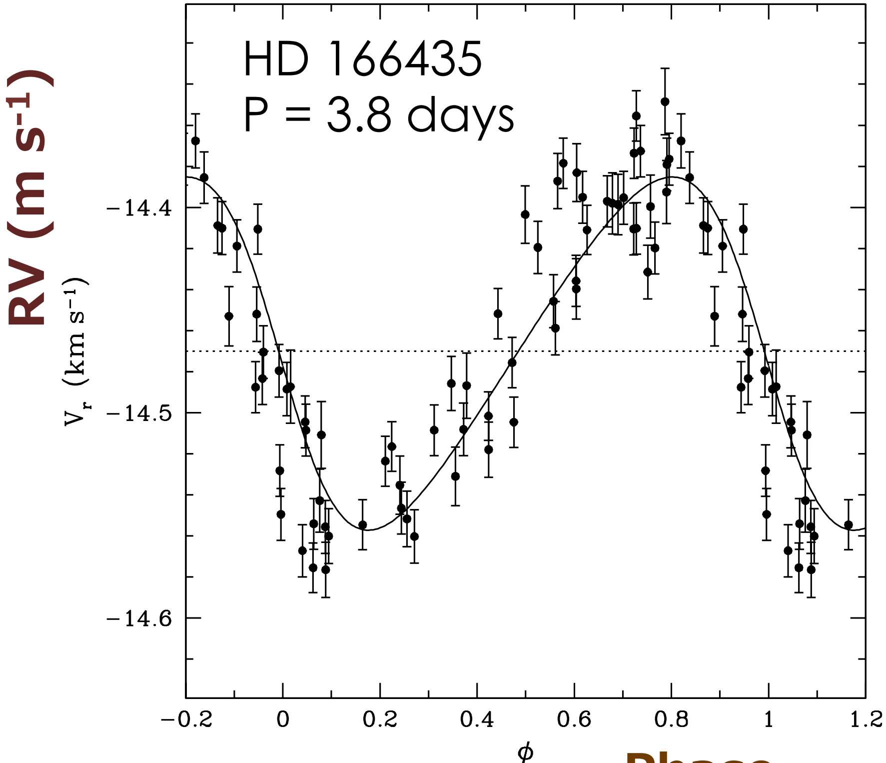


Fig. 2. Phase diagram of the radial-velocity data with a period of 3.7987 day. A binary model is superimposed on the data (solid line). See text for details.

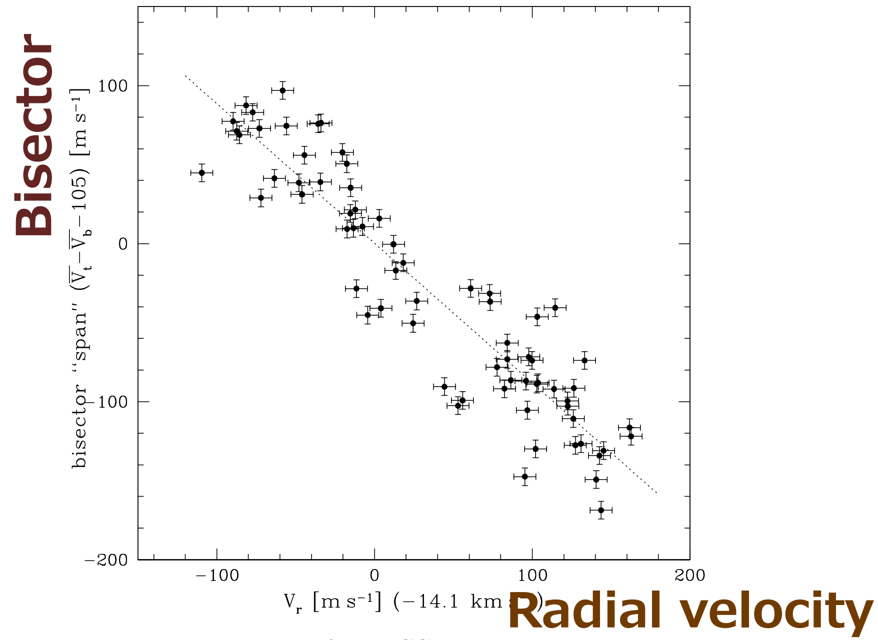
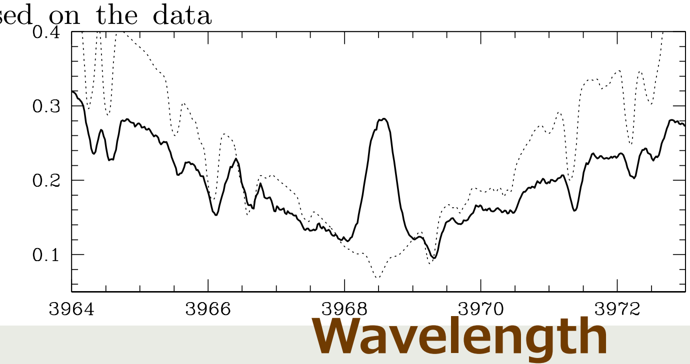
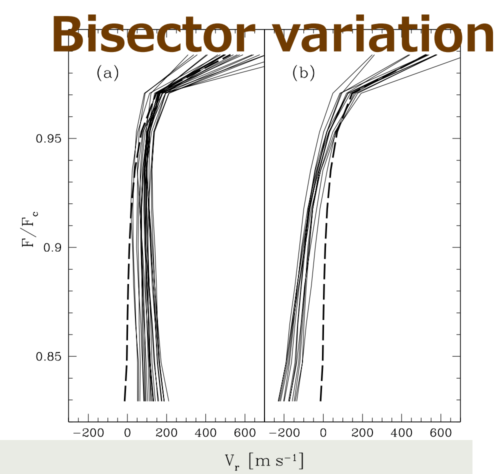


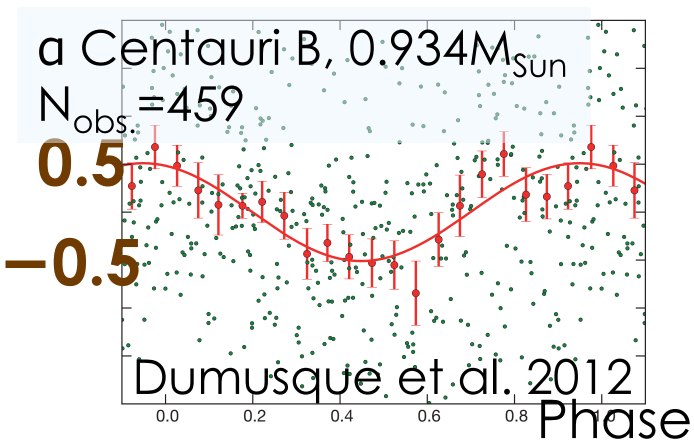
Fig. 7. Radial velocity of each CCF versus the bisector span ($\overline{V_t} - \overline{V_b}$) of the CCF profile. The dotted line is the best linear fit to the data.



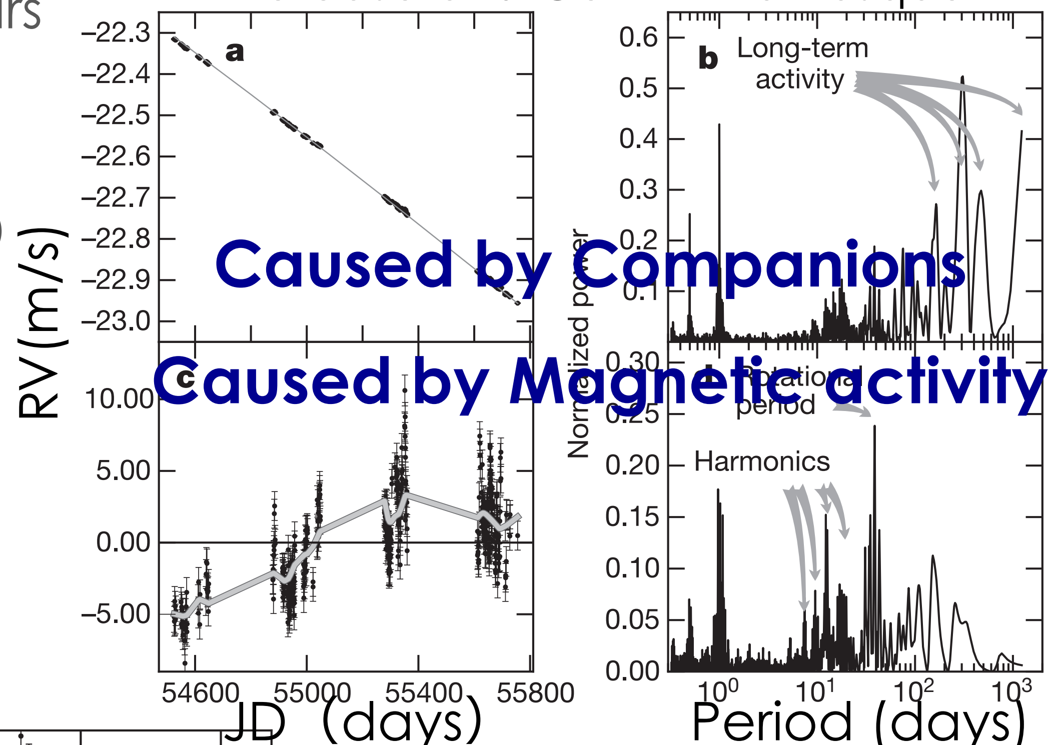


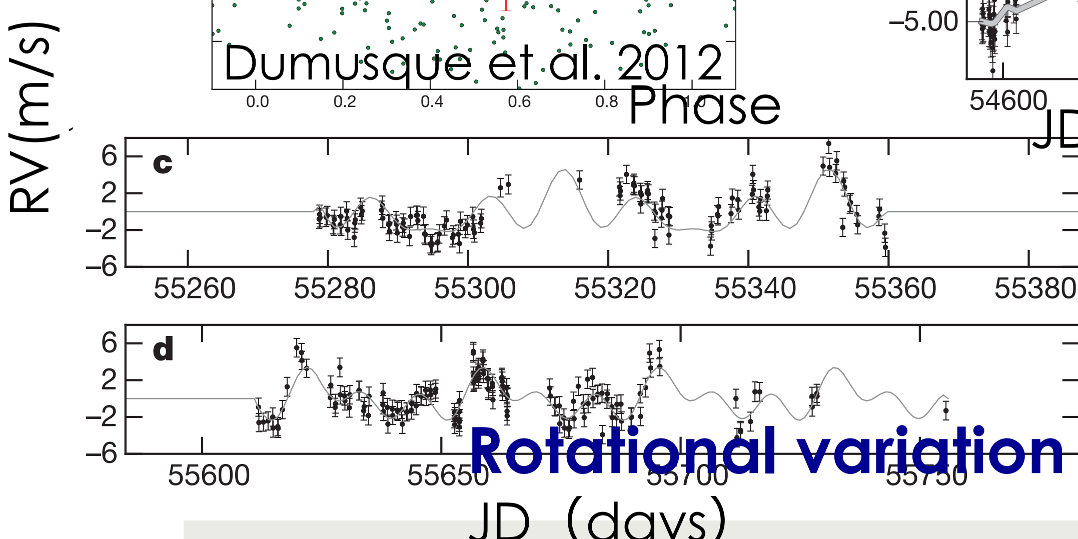
Impact of stellar modulation

- RV variation caused by stars
  - binary signal
  - Magnetic activity
  - Surface (spot, plage etc.)



In the case of α Cen B Dumusque+12





- Must be very careful
  Planet ? or Not? (Hatzes 13)
- Use chrompspheric lines
  and photometric monitor

Impact of magnetic cycle

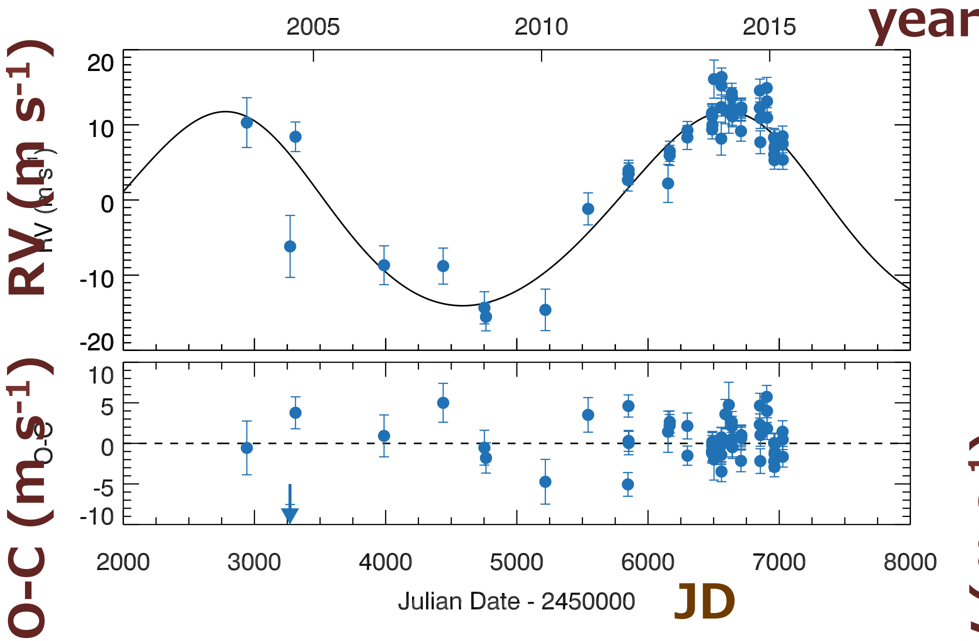


Figure 1　Radial velocity of HIP11915

Upper : ● RV – S_{HK} correlation

Bottom : ● residual

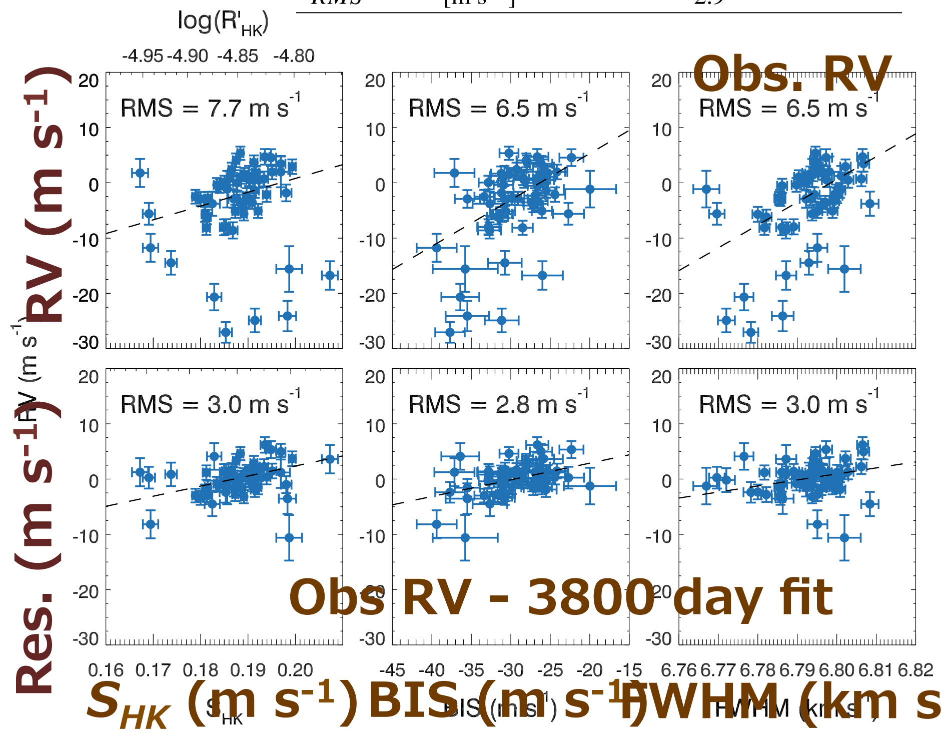
Line : orbital fit、dash : O-C = 0 m/s

Magnetic cycle detected ?

Bedell et al. 2015

Table 1 orbital parameters of HIP11915b

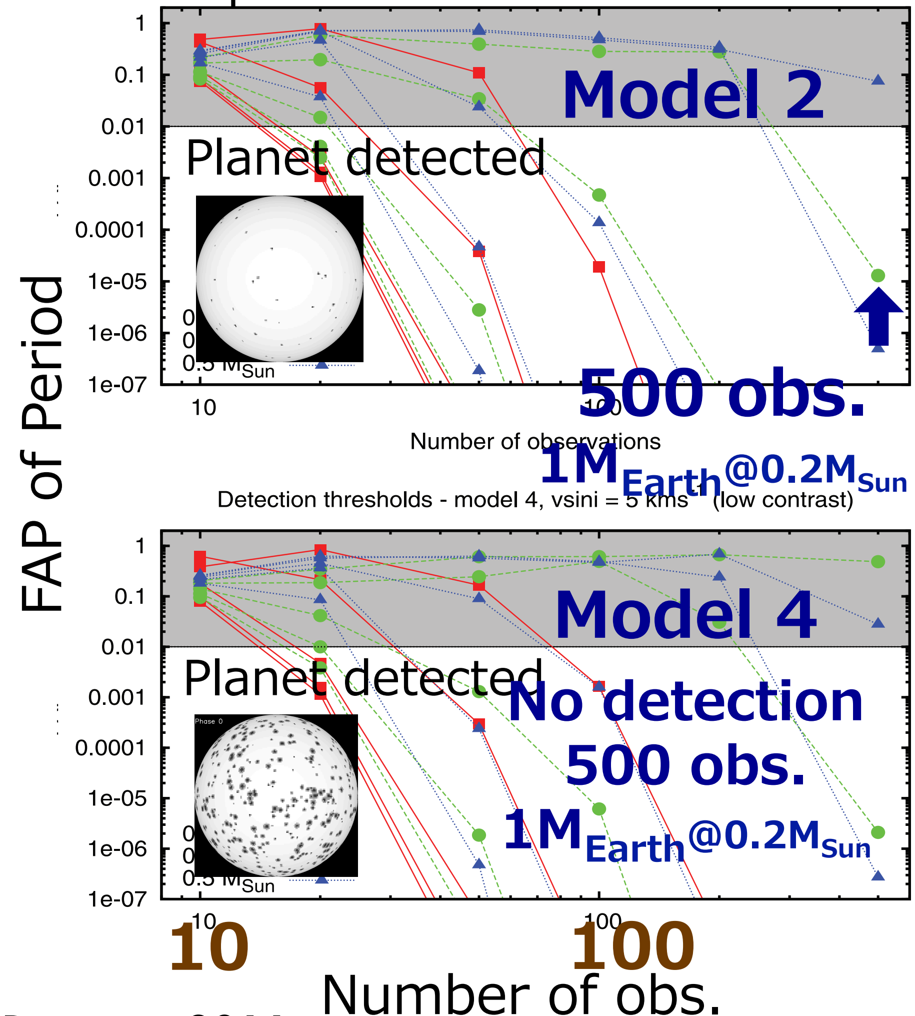
Parameter		Value	Uncertainty
P	[days]	3830	150
K	[m s^{-1}]	12.9	0.8
e		0.10	0.07
$\omega + M_0$	[rad]	3.0	1.3
ω - M_0	[rad]	2.4	0.1
α	[m s^{-1} (unit S_{HK})$^{-1}$]	160	60
C	[m s^{-1}]	-11.0	1.3
σ_J	[m s^{-1}]	1.8	0.4
m_p sin(i)	[M_{Jup}]	0.99	0.06 [1]
a	[AU]	4.8	0.1 [1]
RMS	[m s^{-1}]	2.9	



Impact to RV planet searches

- Simulation to search for Earth-mass planets
  - Modeling of stellar surface
  - Calculate noise on the RVs
  - Calculate number of obs.
- Strategy for Earth-Mass planets
  - Precise RV measurements
    - Precision of ~1m/s
  - Reduce stellar noise
    - Careful sample selection
    - Estimate stellar noise
  - Observe many sample
    - High signal noise ratio
    - Effective observations

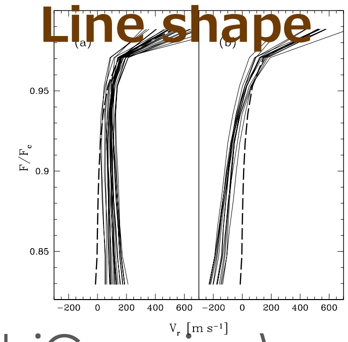
Number of observations for detecting Earth-like planets in HZ Barnes+2011

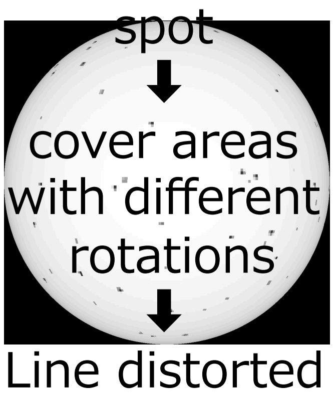


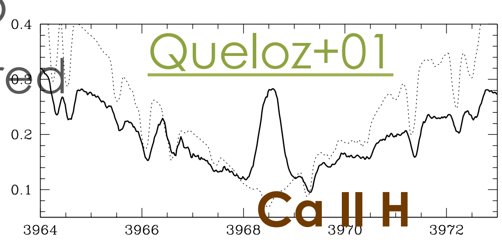
Barnes+2011

Observations of RVs and activity

- RV：Shifts of absorption lines
  - change by activity and planets
- Activity index : S_{HK} , $\log(R'_{HK})$ etc
  - Able to use chromospheric line S_{HK}
    - Other indicators（BIS, FWHM, Vspan, biGaussian)
      - Queloz et al. 2001; Boisse et al. 2011; Figueira et al. 2013
  - Check chromospheric lines in the infrared also
    - correlation of activity index in Optical and Infrared







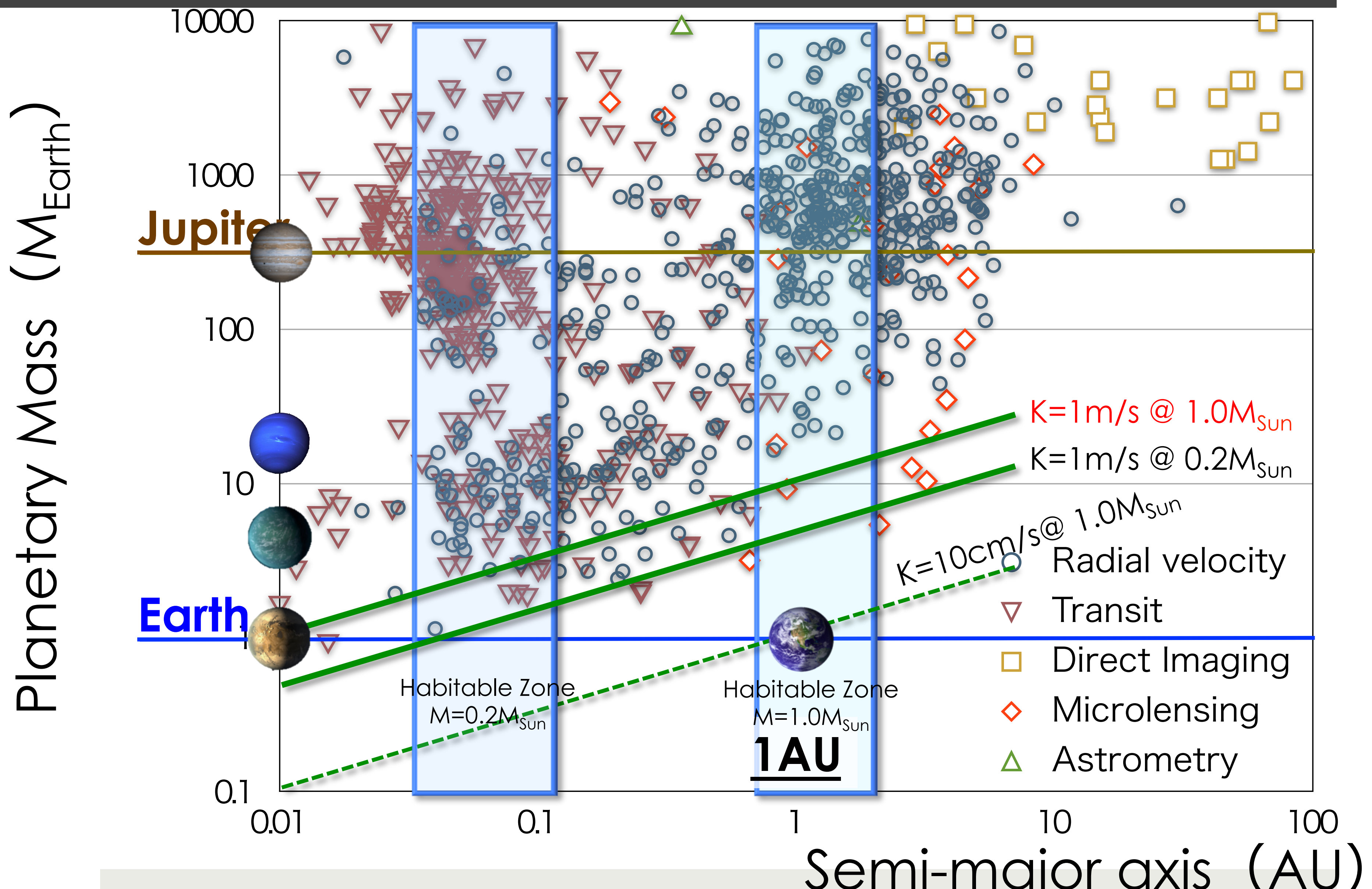
- Line profile on cross-correlation
  - Bisector inverse span (BIS)：position spots
  - Full Width at Half Maximum (FWHM)：size of spots?

Fit activity by indies & collect activity from RV variation
➔ Aim to detect low-mass planets

- Transit method by Kepler and TESS also have some impacts.

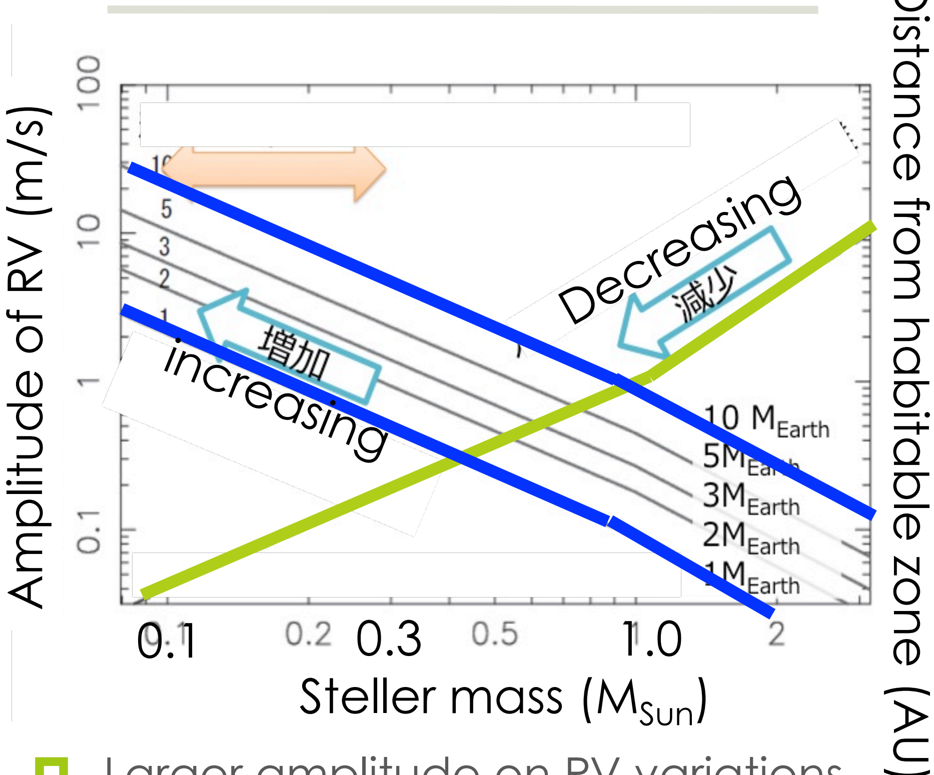
Part 2   InfraRed Doppler project

Current result: Mass – Semi-major axis

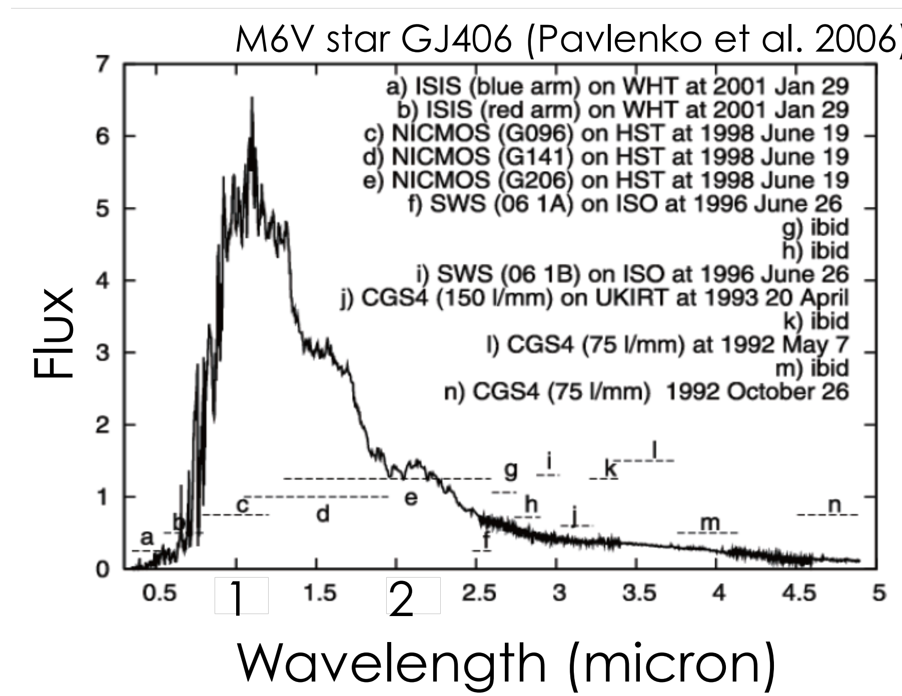


InfraRed Doppler survey of M dwarfs

Amplitude of RV variations & Habitable zone（HZ）



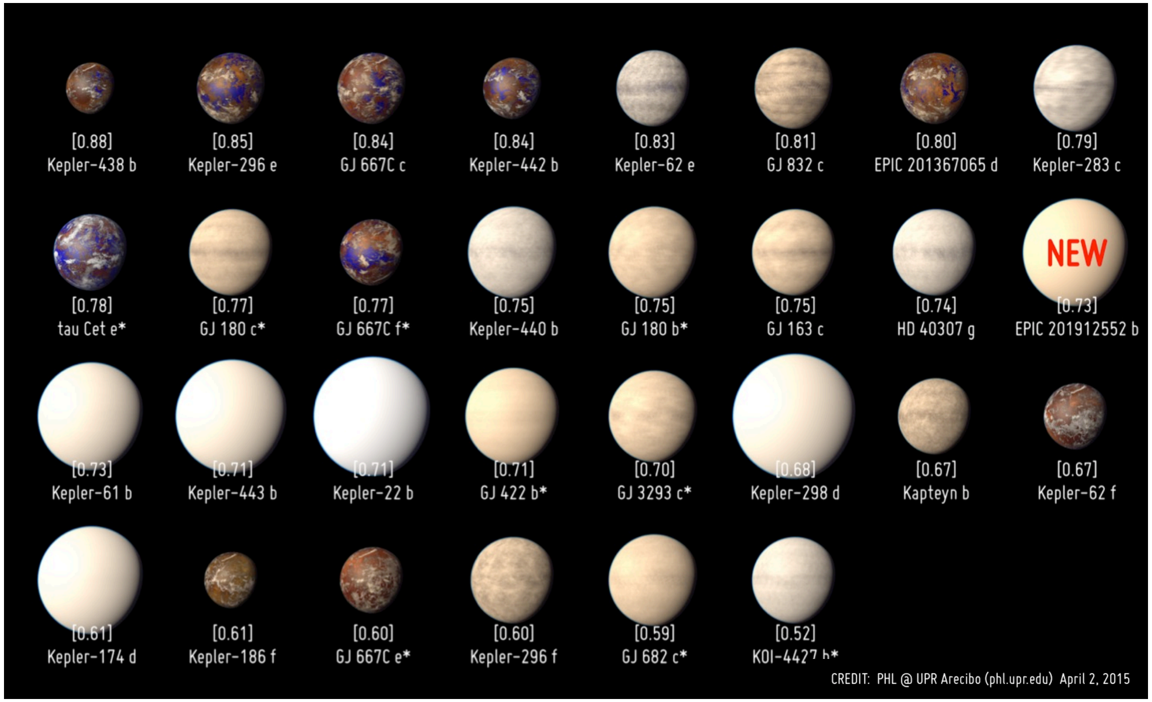
Properties of M dwarfs：Flux peak in near Infrared



- Larger amplitude on RV variations
  - able to detect 1M_{Earth} Planets
- HZ in closer-in orbits（<0.3AU）
- Bright in near-Infrared
  - IR Doppler most powerful tools
- Many stars in the solar neighborhood

Current results: HZ Earth-like planets

0.1-10 Earth Masses or 0.5-2.0 Earth Radii in the Habitable zone



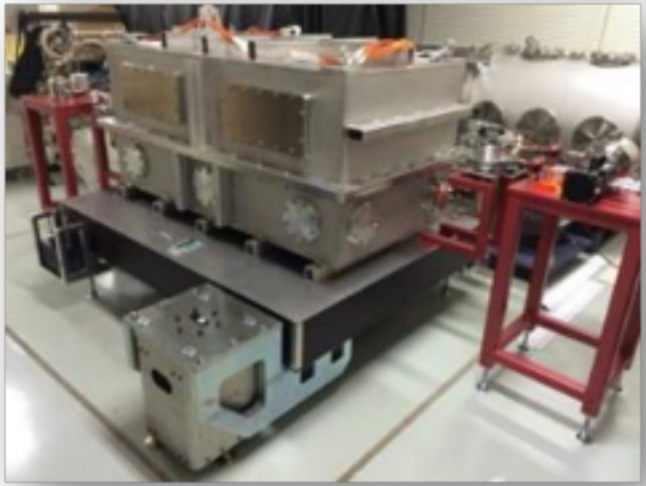
- Planets detected by Doppler method
  - Around late-type stars
  - Planetary mass > 3.8 Earth mass
- Planet detected by Kepler planets
  - Very far from Earth
    - Difficult to have follow-up obs.
    - not determine planetary mass

Name	Mass (Earth)	Radius (Earth)	Temperature (K)	Period (days)	Distance (light yr)
Kepler-438 b	4.0 - 1.3 - 0.6	1.1	276	35.2	473
Kepler-296 e	12.5 - 3.3 - 1.4	1.5	267	34.1	1692
GJ 667C c	3.8	1.1 - 1.5 - 2.0	247	28.1	24
Kepler-442 b	8.2 - 2.3 - 1.0	1.3	233	112.3	1115

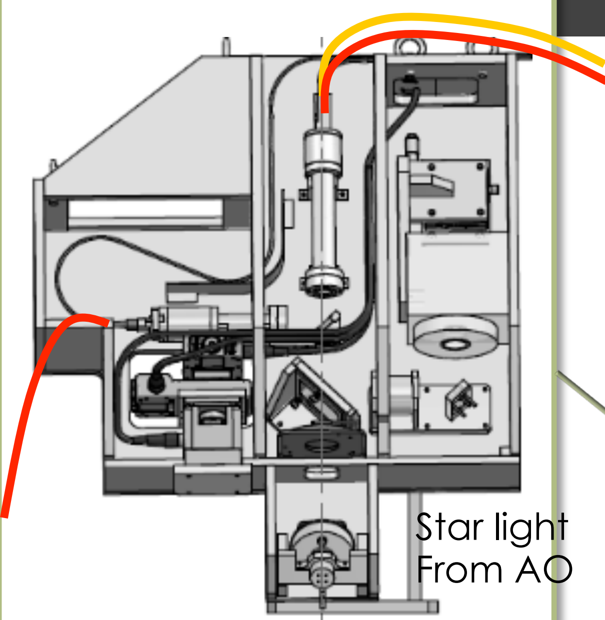
1. Can not find any Earth-like planets in solar neighborhood
2. Too small number of planets for statistical understanding

InfraRed Doppler Project

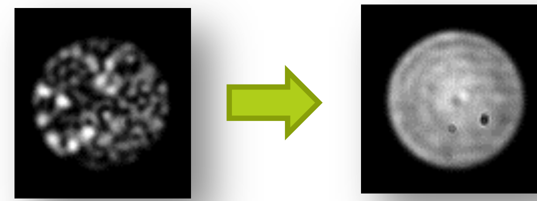
- What is IRD?
  - **near infrared high dispersion spectrograph** for the Subaru telescope
  - For Exoplanet searches by the Doppler technique
- Main goals of IRD
  - **Discoveries of Earth-mass planets** around nearby M type dwarfs
  - M dwarfs, characterization of exoplanet's atmospheres, etc.
- Uniqueness of IRD
  - Wide Wavelength coverage：
    0.97-1.75um　(Y, J, H–band)
  - Resolution： 70,000 (high resolution)
  - Calibration： Laser frequency comb
  - **RV precision ~ 1m/s**
    - → Can detect Earth-Mass planets in HZ around late-M dwarfs



Overview of IRD instrument



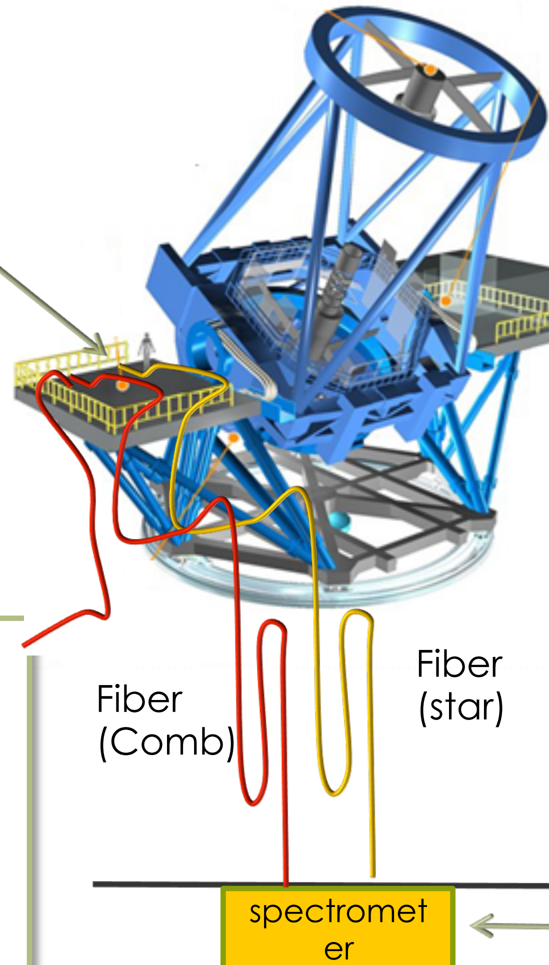
Fiber injection system
(AO bench)



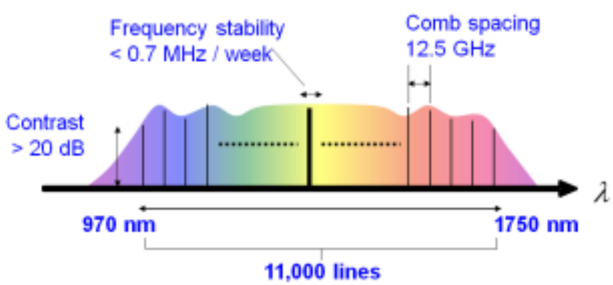
Mode scrambler

Resolution: R=70000
Wavelength: 0.97-1.75um
Cryo: 70K (detector), 200K (optics)

Spectrometer system
(Coudé room)



Coudé Room

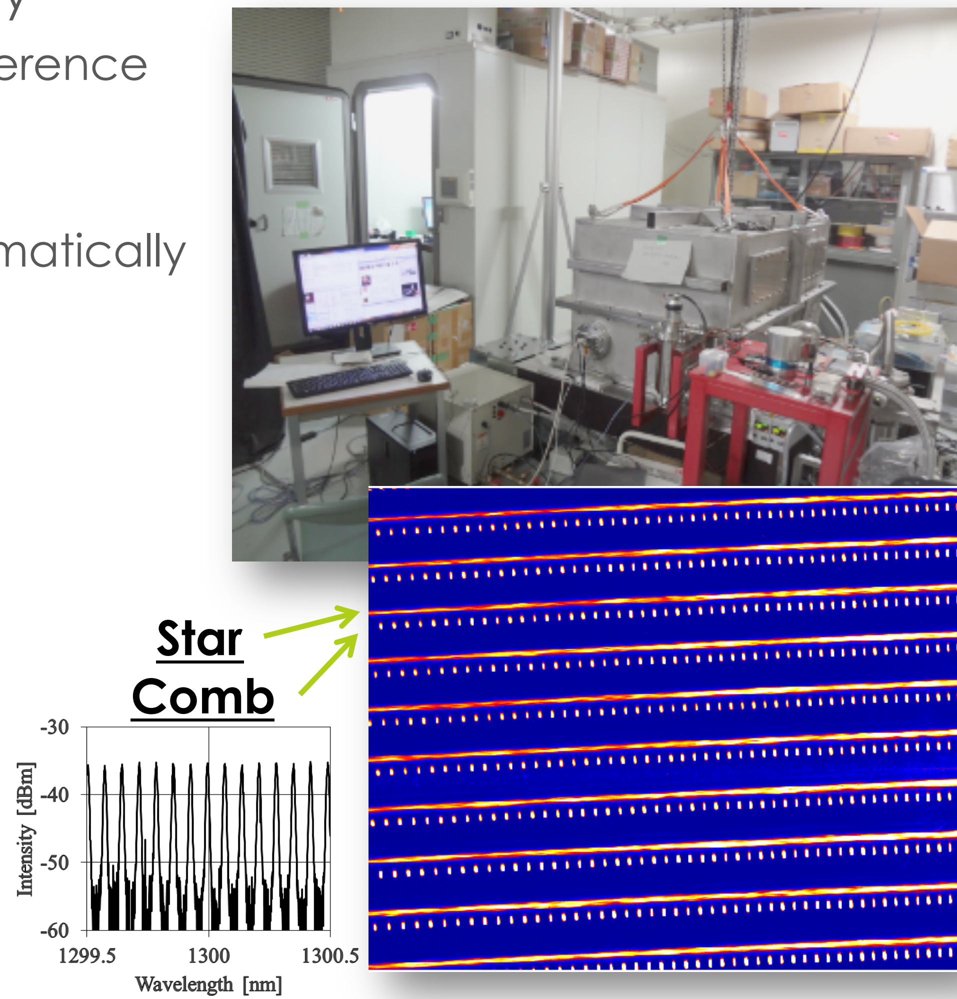


Laser frequency comb
(IR Observing floor)

IRD survey : ANALYSIS

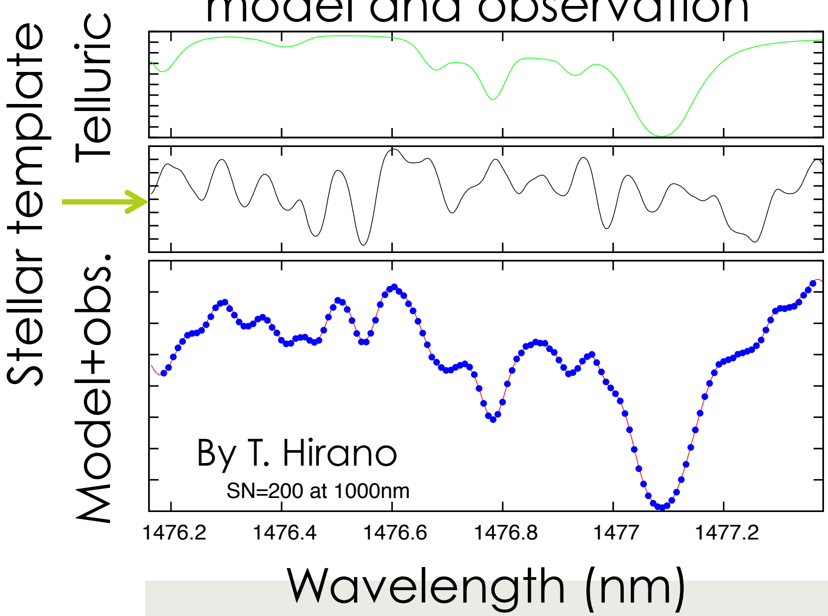
- NIR High dispersion spectroscopy
  - Stellar spectra + wavelength reference
- Radial velocity measurements
  - Fit models to Observations automatically
  - RV is a parameter of the fit

Simultaneous reference method



Take spectra of comb (wavelength reference) and stars simultaneously

Analysis: simulated spectrum of model and observation



IRD survey : CONCEPT

Difficult to detect Earth-mass planet around solar-type stars

Late-M type dwarfs（mainly M4-M7、0.1-0.3 M_{Sun}）

- A large number of sample stars in solar neighborhood
- **Easier to detect Earth-Mass planets in Habitable zone (HZ)**
  - large amplitude (K=0.5-2m/s) and short period (P<40days)
  - A flux peak of the stars is in infrared ➔ High efficiency
- **Only an IRD survey is reachable to Earth-like planets**
  - Subaru can observe faint low-mass stars with 1 m/s
  - Probability of a transit is higher than solar type stars

Main scientific goals of IRD/Subaru planet search

1. First discovery of Earth-mass planets in habitable zone
2. Statistical understanding of Earth-mass planets around low-mass stars

IRD survey : DOPPLER SURVEYS

- Survey 0 : Screening Doppler survey
  - sample : <150 late-M stars (<11.0 mag, 0.1-0.3 M_{SUN})
  - strategy : ~4 RV observations for each star

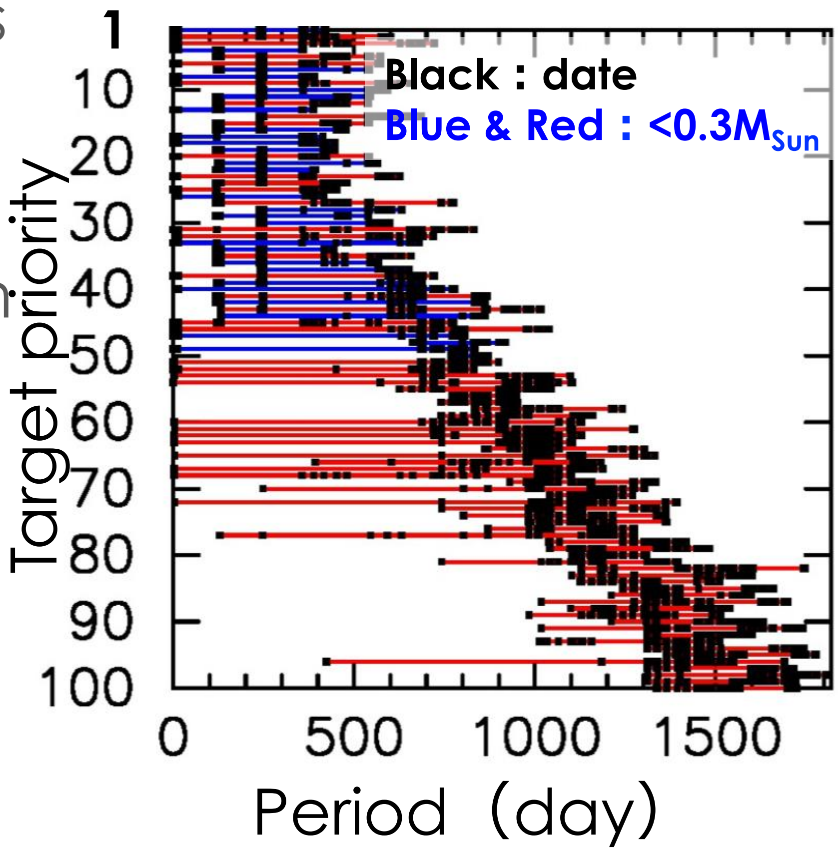
- Survey 1 : QUICK and FREQUENT Doppler survey in FIRST yr
  - sample : **~30 Brightest Low-mass stars (<9.0 mag, 0.1-0.2M_{SUN})**
  - strategy : **>80 RVs/star in ONE year**

- Survey 2 : NORMAL Doppler survey from second year
  - sample : **~70, ~9-11 mag, 0.1-0.3 M_{SUN}**
  - strategy **: >50 (>0.2M_{SUN}) or 80 (<0.2M_{SUN}) RVs/star for 2-4 yrs**

- Additional Survey : TRANSIT survey of IRD-detected planets
  - By ground-base facilities (OAO, IRSF etc.) and the TESS satellite

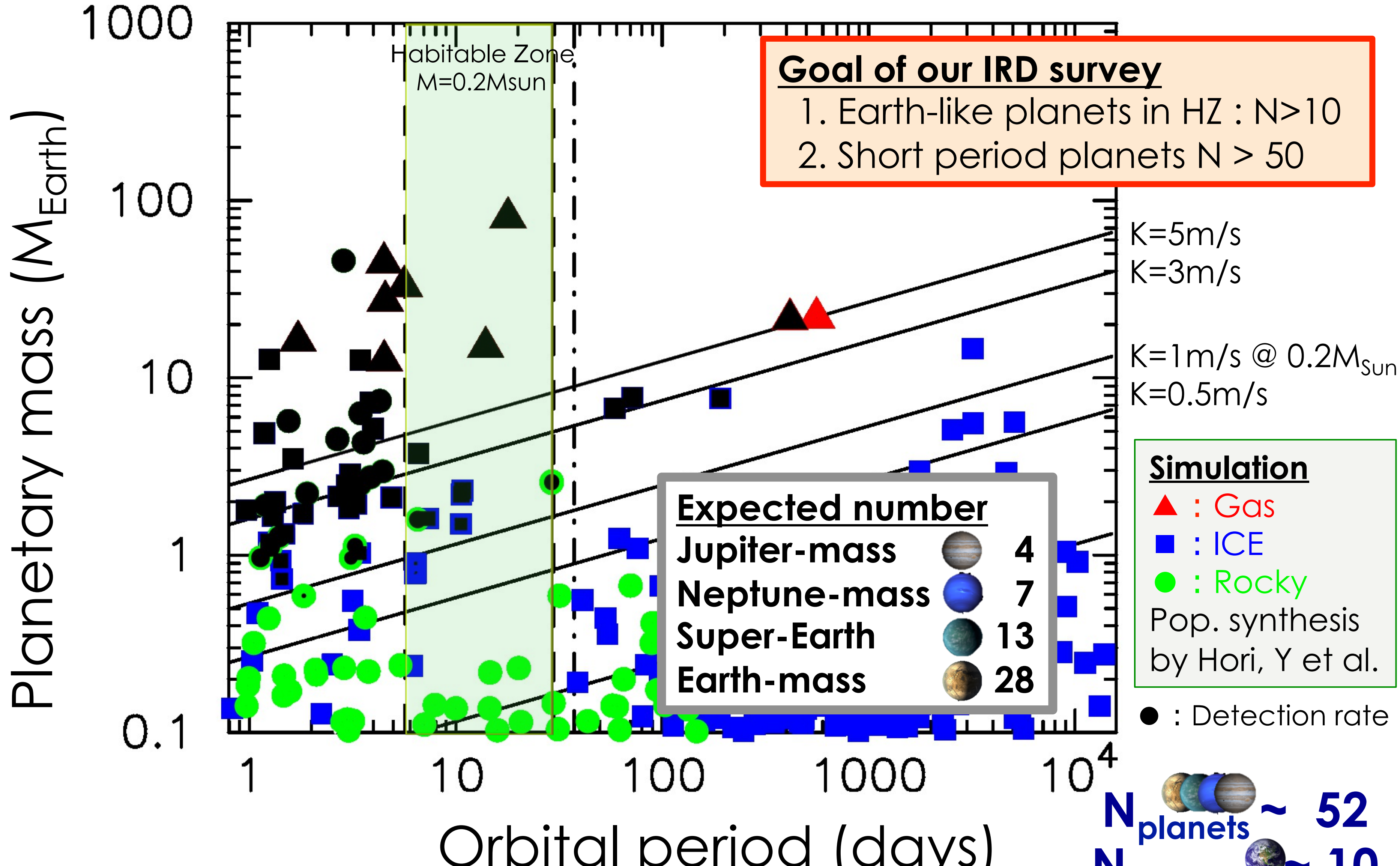
IRD survey : OBSERVATION PLAN

- An intensive Doppler (Radial velocity) survey
  - Start in 2017
  - Number of requested nights
    - 170 nights
  - Survey period : 5 years
    - Subaru Strategic Program
  - Number of observations
    - ~80 times, SNR >100



- Requested Schedule
  - mainly bright nights
  - ≤ 70 half nights/year
  - 0.5 nights x 7times x 9-10 runs / year

IRD survey : DETECTABLE PLANETS



IRD survey : BRIEF SUMMARY

- IRD : InfraRed Doppler instrument for the Subaru telescope
  - Wavelength coverage : 0.97-1.75um (Y, J, H-band)
  - Wavelength Resolution : R ~ 70,000 (max)
  - Wavelength Calibration : Laser Frequency comb
  - Radial velocity precision : ~1 m/s
- **DOPPLER SURVEY : START in 2017, END in 2022 with SSP**
  - FIRST light of IRD : Summer 2016
- TARGETS : ~100 Late-M dwarfs (M4-M7)
  - nearby Low-mass stars : 0.1-0.3 M_{SUN} , <25pc
  - Inactive old stars : >Gyr, No Ha emission
- GOALS : **>50 planets**& **>10 Earth-like planets** in the Habitable zone
  - Because of small sizes of host stars and small semimajor-axis of planets in HZ, probability of a transit is high and make their characterization.

IRD's unique planetary science

- Earth-Mass planets around **Late-M dwarfs**

- Characterization of exoplanets
- Confirmation of transiting planets

- Planets around **Young stars** w/ and w/o disks
- Planets around **Brown dwarfs**

many other ideas…

Part 3 To search for stable stars

IRD survey : STRATEGY

1. **Careful sample selection**
   - Stars with low stellar noise in RV variation
   - Stars which can achieve RV precision of ~1 m/s

2. **High cadence and frequency Doppler survey**
   - To cut stellar noise and instrumental systematic noise
   - To make observing period shorter

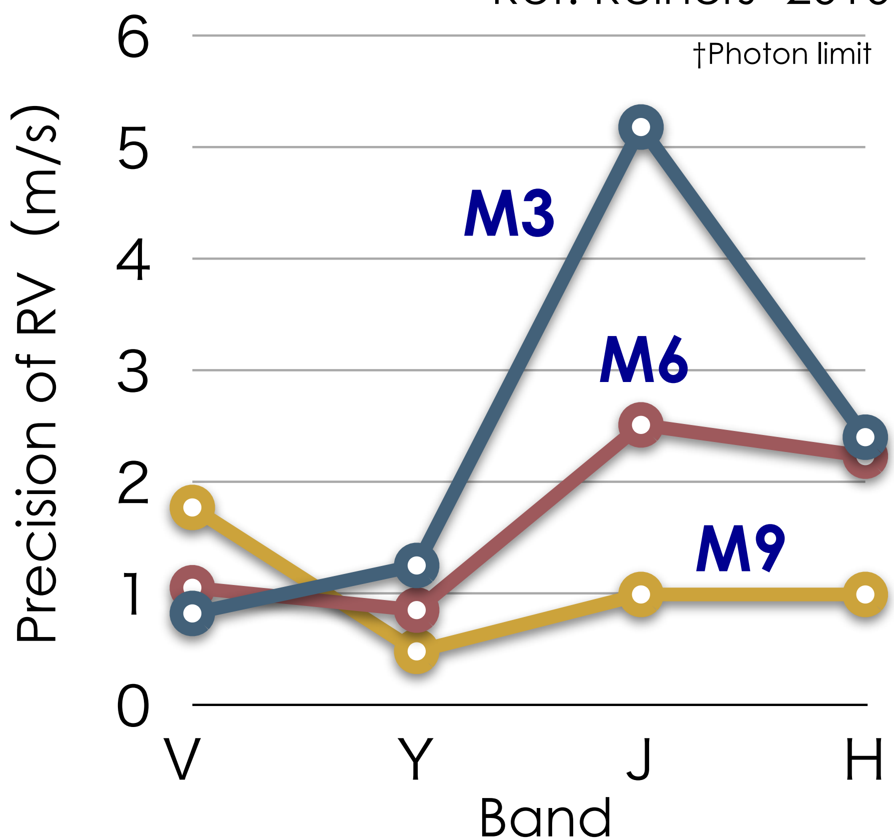
3. **Simultaneous RV & activity diagnostic Analysis**
   - To verify RV modulation caused by stellar activity

IRD survey :　SAMPLE CRITERIA

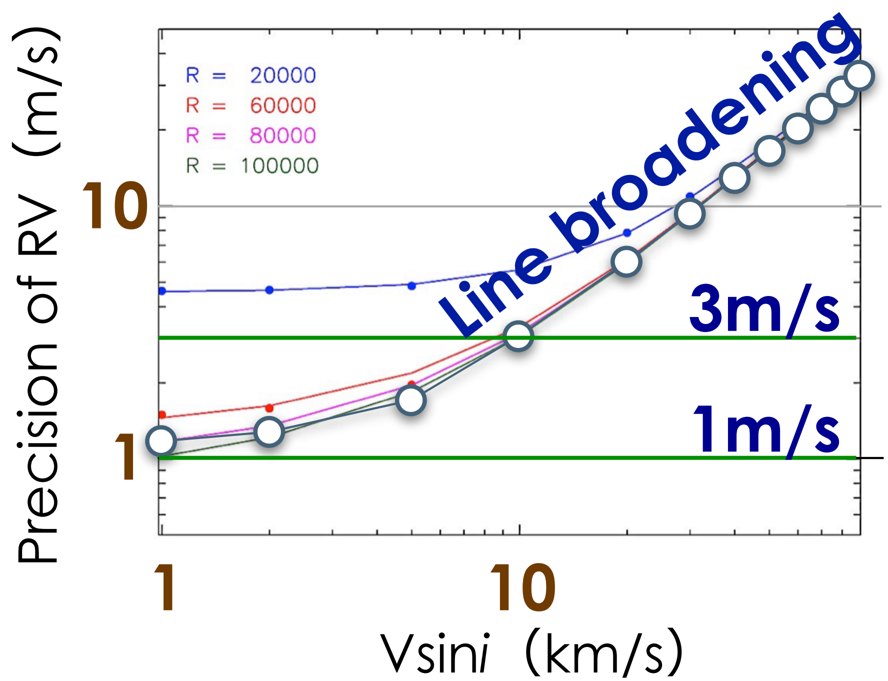
- ◆Stars with observed parallax and magnitude
  - ◆known other basic parameters
- ◆Suitable stars for precise Doppler survey
  - ◆Stars with precise Doppler measurements
    - ➔ **Small vsini and late-type M dwarfs**
      - ➔ Rotation、Vsini、spectral type
  - ◆ Star with Small stellar jitters in RV variation
    - ➔ **Late-M with weak stellar activity**
      - ➔ XUV、Ha emission、rotation period
- ◆Toward scientific goals
  - ◆low-mass stars、single　etc.

Precision of RV measurements

Expected precision of RV measurements from stellar spectra
M3(○), M6(○), M9(○)
SN~300@Y-band, Vsin*i*=0km/s, R=80,000
Ref. Reiners+2010



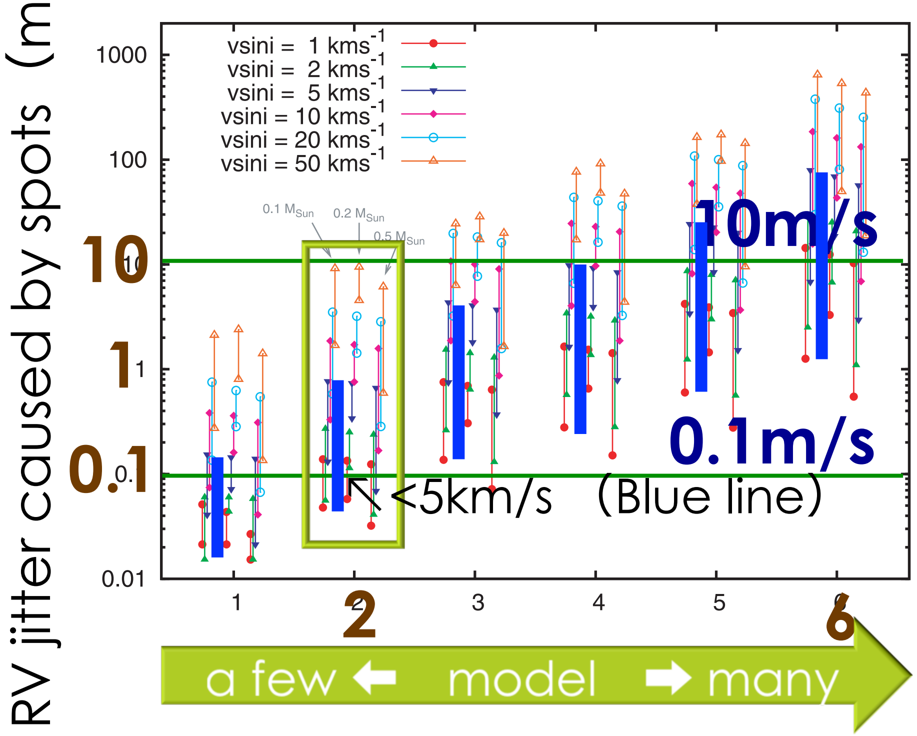
SN~100, M5, Y-band, Reiners+2010



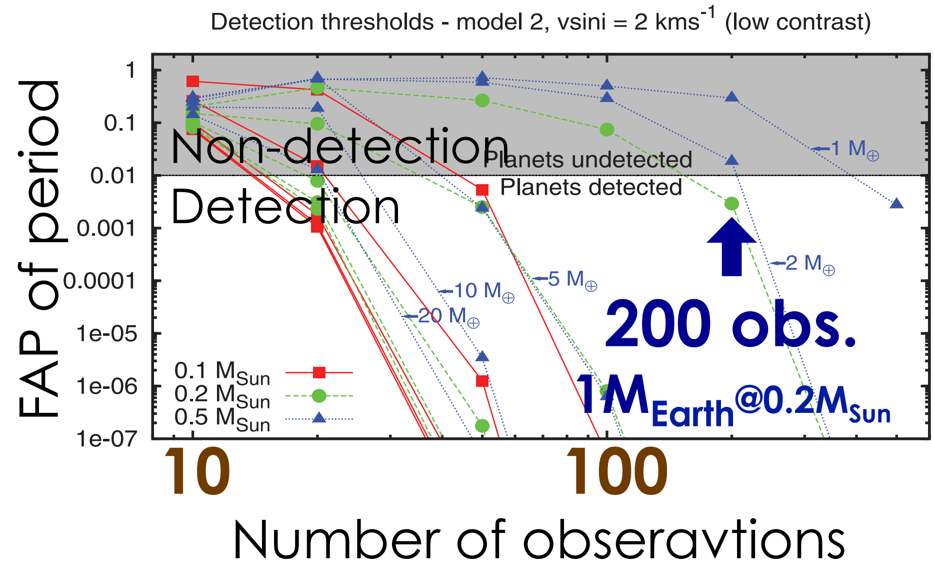
Late type & slow rotation stars can achieve a high precision with 1 m/s !

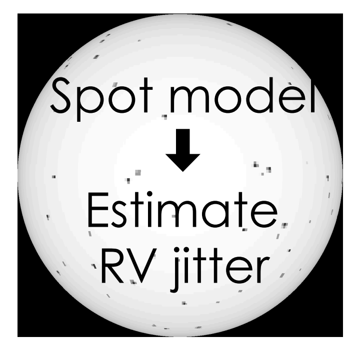
Simulation of RV jitter by spots

Spot model and rotation and RV jitter
0.1-0.5M_{Sun} stars, Barnes+2011



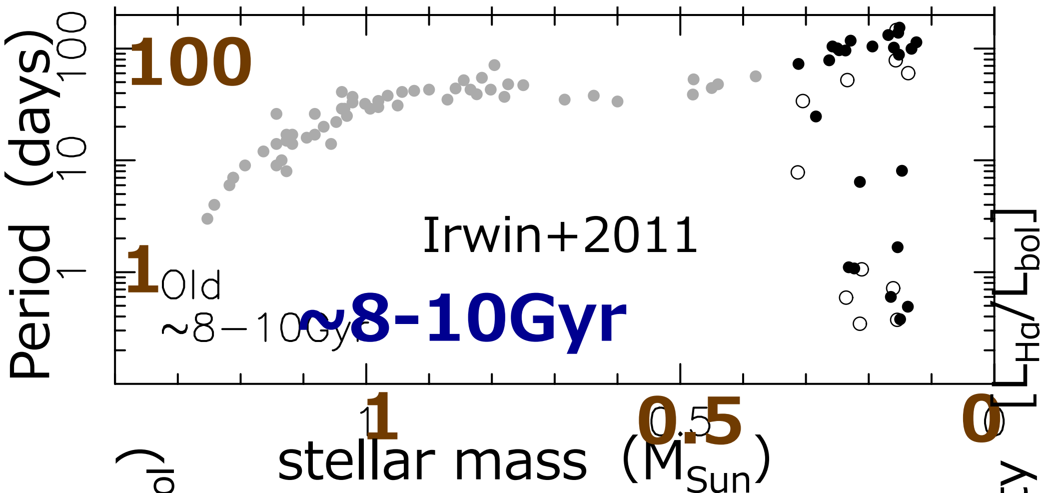
Required number of RV observations which can detect Earth mass planets
Barnes+2011 Vsin*i*=2km/s, RV_{error} =1.2m/s



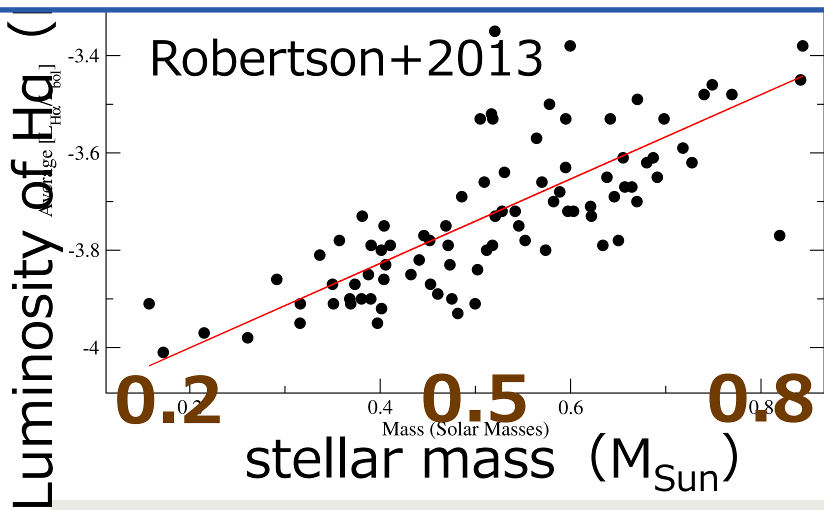


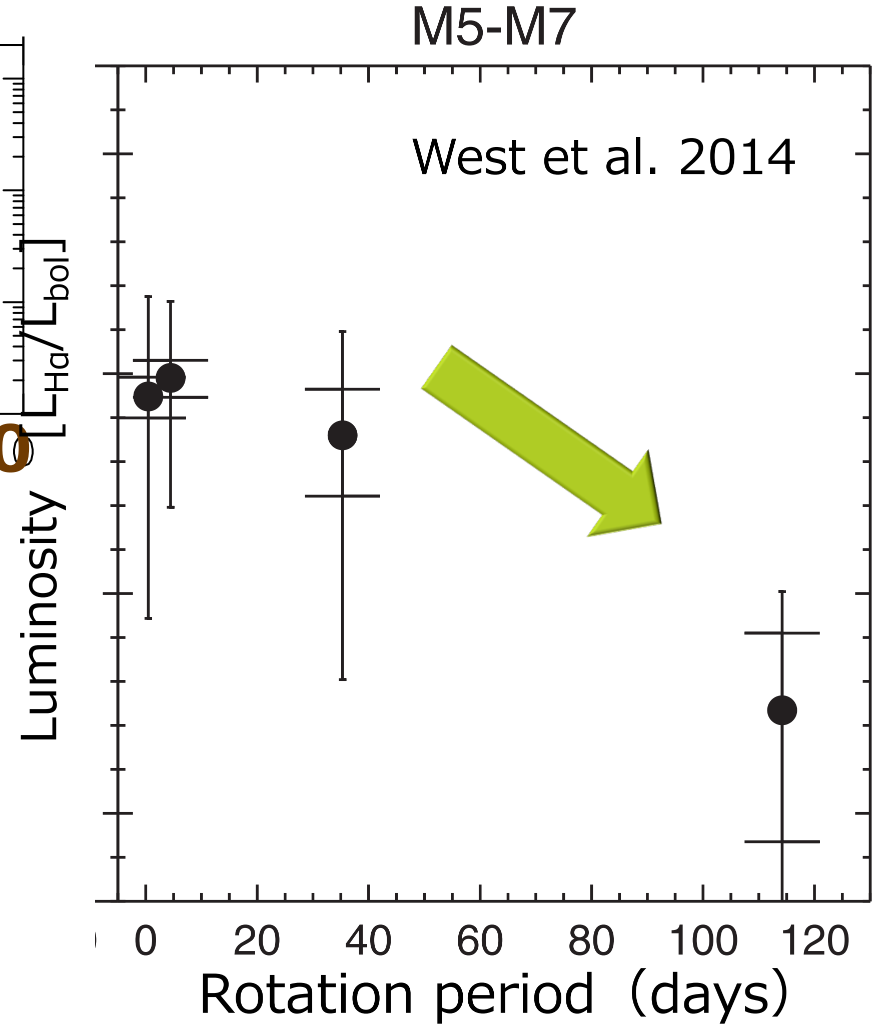
Because of low stellar mass & small values of RV jitter, requested number of RV observations for detections of Earth-mass planets in habitable zone is small.

What parameters ?



For late-M dwarfs without detections in XUV have weak activity





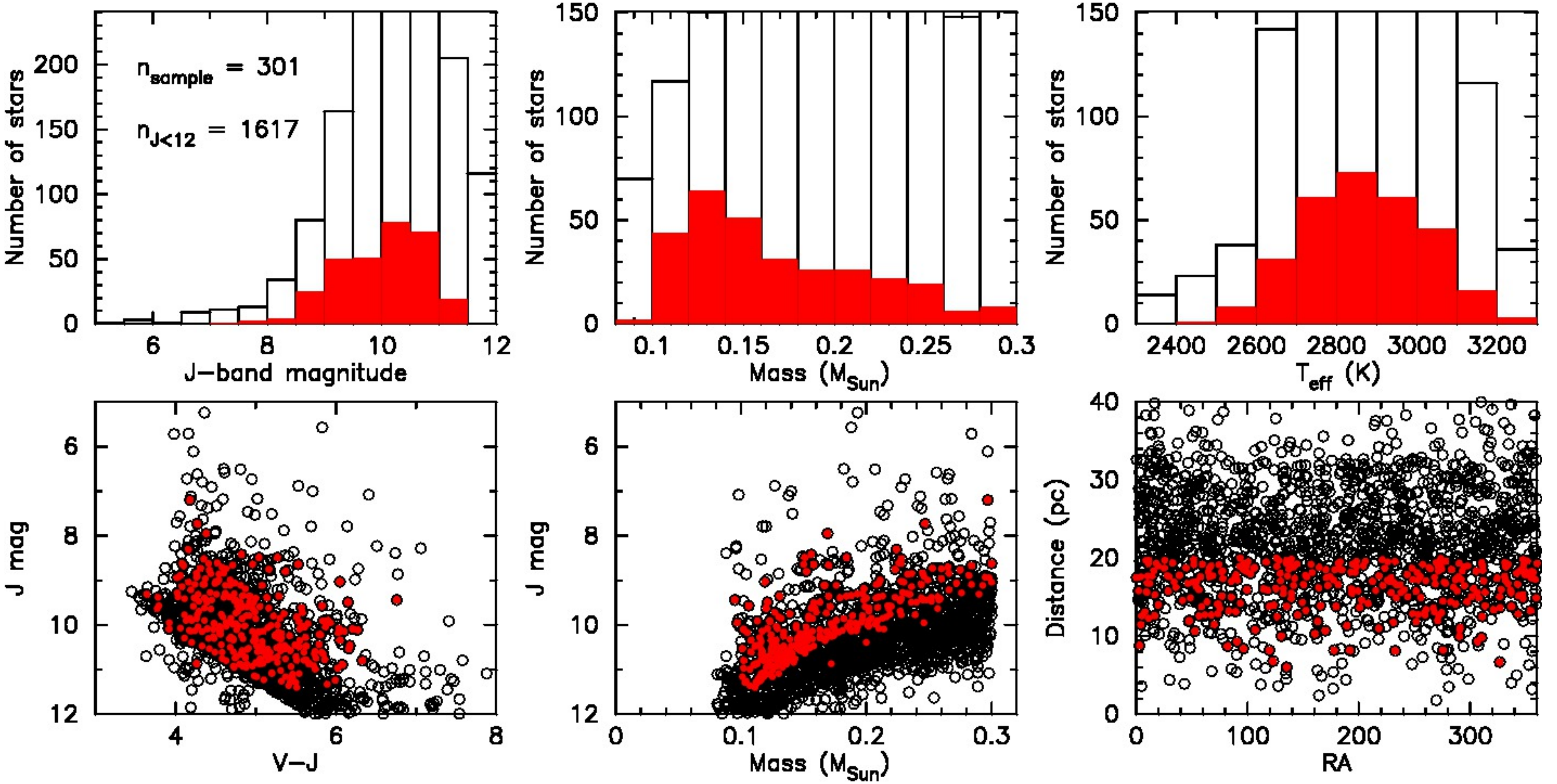
Criteria of suitable targets
stars with weak XUV & Hα

IRD survey : INPUT CATALOG

- **Declination (Dec.>0)** : basic information
  - LSPM-North proper-motion catalog nearby stars (Lepine 2005)
- **Brightness (J<11.0)**: Exclude fainter stars and too high and low temperature stars
  - An All-sky catalog of Bright M Dwarfs (Lepine+2011)
  - simbad
- **Trigonometric Parallaxes (0.1-0.3M_{Sun})**: Exclude high-mass (early-type) stars
  - LSPM-North proper-motion catalog nearby stars (Lepine 2005)
  - Trigonometric Parallaxes for 1,507 Nearby Mid-to-late M-dwarfs (Dittmann+2013)
- **Activity indicators (non Hα, X-ray, UV active)** : Exclude active stars
  - An All-sky catalog of Bright M Dwarfs (Lepine&Gaidos 2011)
  - A Spectroscopic Catalog of the Brightest (J<9) M Dwarfs in the Northern Sky (Lepine +2013)
  - Screening observation by ourselves (NOW)
- **Binarity check (single star)**: Exclude multiple stars
  - The Washington Visual Double Star Catalog (Mason+ 2001-2014)
- **Target check**: Target list of other planet searches:
  - California, MacDonald, HARPS, MEarth, KOI

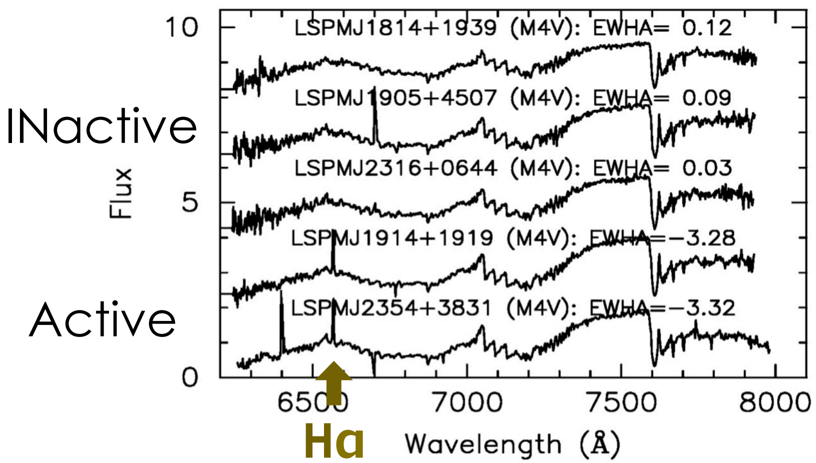
IRD survey : SAMPLE

- sample candidate： 300 stars
  - J~7-11.5 mag、Mass~0.1-0.3M_{Sun} 、**D<20pc**
  - Exclude flare, variable, XUV, Hα emission stars



IRD survey : PILOT OBSERVATION

- To select suitable sample
  - Select stars with weak X-ray, UV
  - **OAO/KOOLS observation**
    - **To check activity by observing Hα line**
    - **Weak Hα ≒ inactive**



  - Check rotation and binarity etc.
    - single stars, vsini < 4 km s^{-1}
- Select best ~100 stars
  - From our observation and literatures

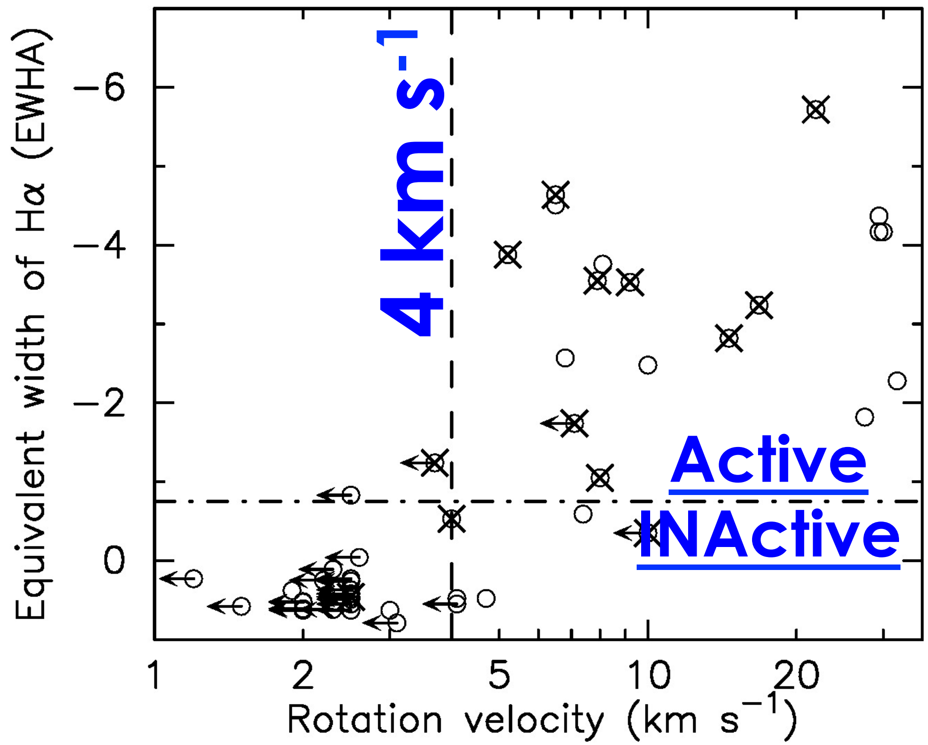


Fig. Equivalent widths of Hα vs Rotation velocity of late-M dwarfs

Most of inactive stars are <4 km/s. Rapidly rotation stars would have strong Hα emission.

× : XUV emission stars

Hα, UV, X : Lepine+13

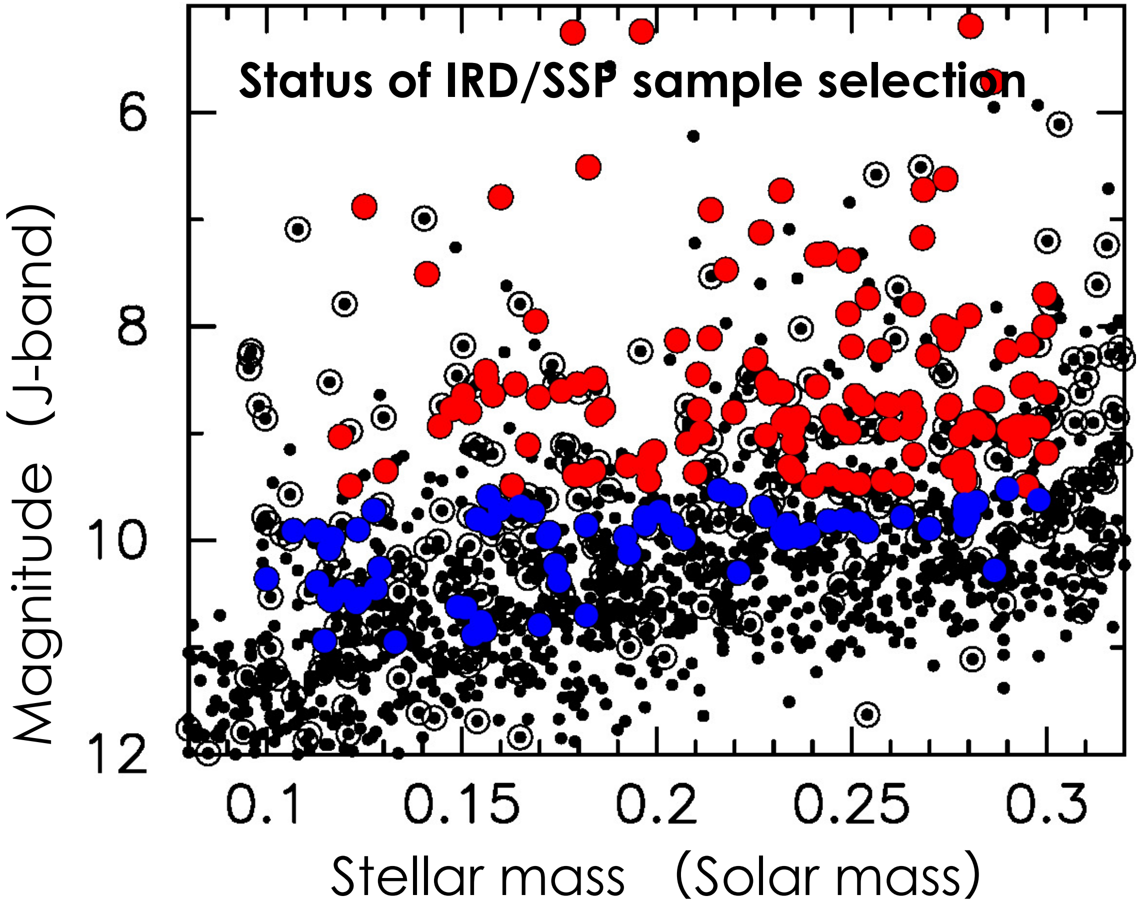
V sin*i* : e.g. Jenkins+09

dash: 5 km s^{-1}, dot-dash : EWHA=-0.75

IRD survey : SAMPLE SELECTION

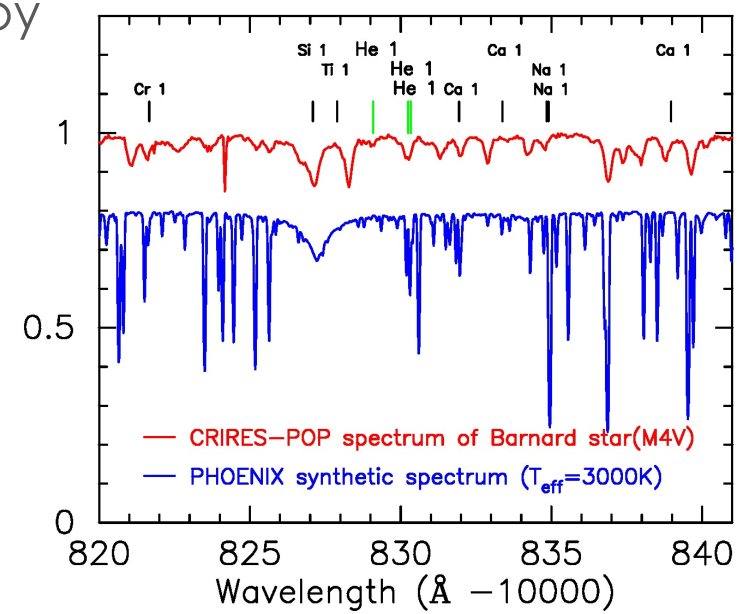
- ~100 Late-M dwarfs with observed parallaxes for
  - Survey 1 : QUICK and FREQUENT Doppler survey in FIRST year (Red)
  - Survey 2 : NORMAL Doppler survey from second year (Blue)

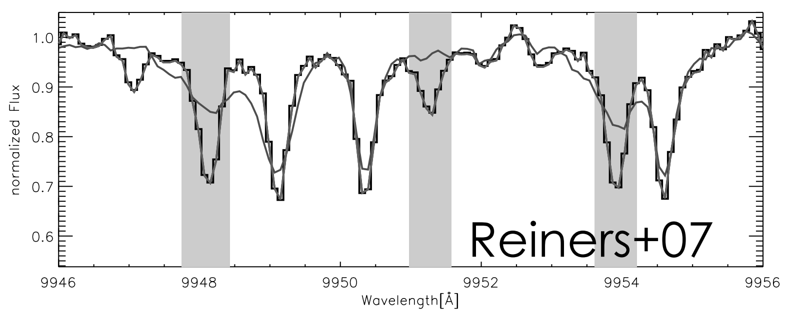
- Sample criteria
  - **Declination (Dec.>0)**
  - **Brightness (J<11)**
  - **Parallaxes**
    - **0.1-0.3M_{Sun}**
  - **Activity indicators**
    - **No Ha, X-ray, UV**
  - **Excluding**
    - **visual binaries**
    - **Flare stars**
    - **Variable stars**
    - **e.g. BY-Dra**



InfraRed activity indicators

- Monitoring of high dispersion spectroscopy
  - Check chromospheric lines
    - He I 10830Å
    - Paschen series
      - β(12800Å),γ(10938Å),δ(10049Å)
  - Check magnetic field
    - FeH lines @9900Å => Zeeman effect
  - Line shape analysis
- Correlation between Hα and Infrared
  - observe Hα in intermediate dispersion spectroscopy
- Photometric monitoring
  - Rotation period

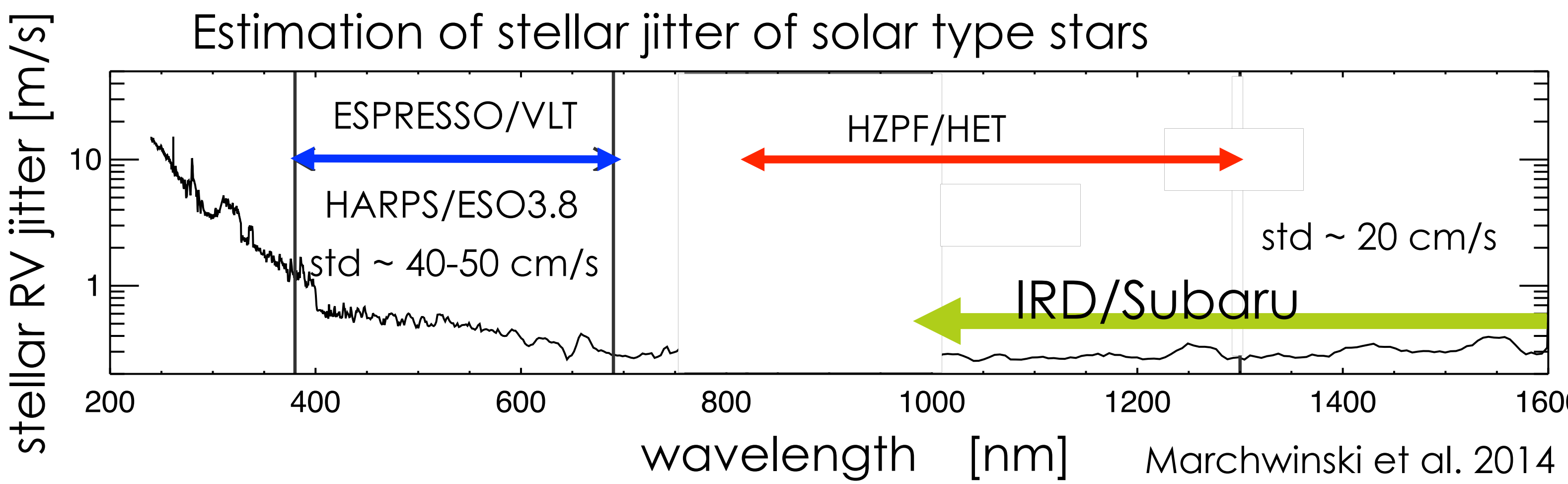




We need to check correlation between infrared and optical chromospheric lines

Toward second Earths

- **Earth-mass planets around solar type stars by precise RV survey**
  - Stellar jitter in infrared is lower than in optical.



  - To detect second Earths
    - We need to have large Doppler survey of FGK-type stars
      - Long term and high SNR
  - IRD is one of possible instruments attached to 8m telescope

Observation of exoplanets and activity

- Stellar activity is known to be a large noise for Exoplanet searches

- Rotation modulation
  - RV variation: Spots, pluge, and so on
  - Effect of the activity depends on stellar type of the star
  - Period of the modulation ~ rotation period
- Magnetic activity
  - RV variation: Convection caused by magnetic activity
  - long-term Solar-like magnetic activity cycle

- Toward Earth-mass planet, we need to select sample stars with low surface activity and cancel the activity of the stars

Take home messages

- IRD is only an instrument to reach to Earth-like exoplanets
  - by observational astronomy in the world in several years.
  - We can also use the instrument for other ideas.
- Apply to SSP, Subaru Strategic Program and start the survey in 2017
  - Require 170 nights for the IRD survey for 5 yrs at the Subaru telescope
- We need your support for a success of the proposal.

Search for Earth-like Exoplanets !

Time to investigate Exo-Earths

and stellar activity !

- If you are interested in the IRD survey please join members of the proposal.
  - **Observers and Theorists also welcome!**